Pulsars, Transients, Parkes and the SKA

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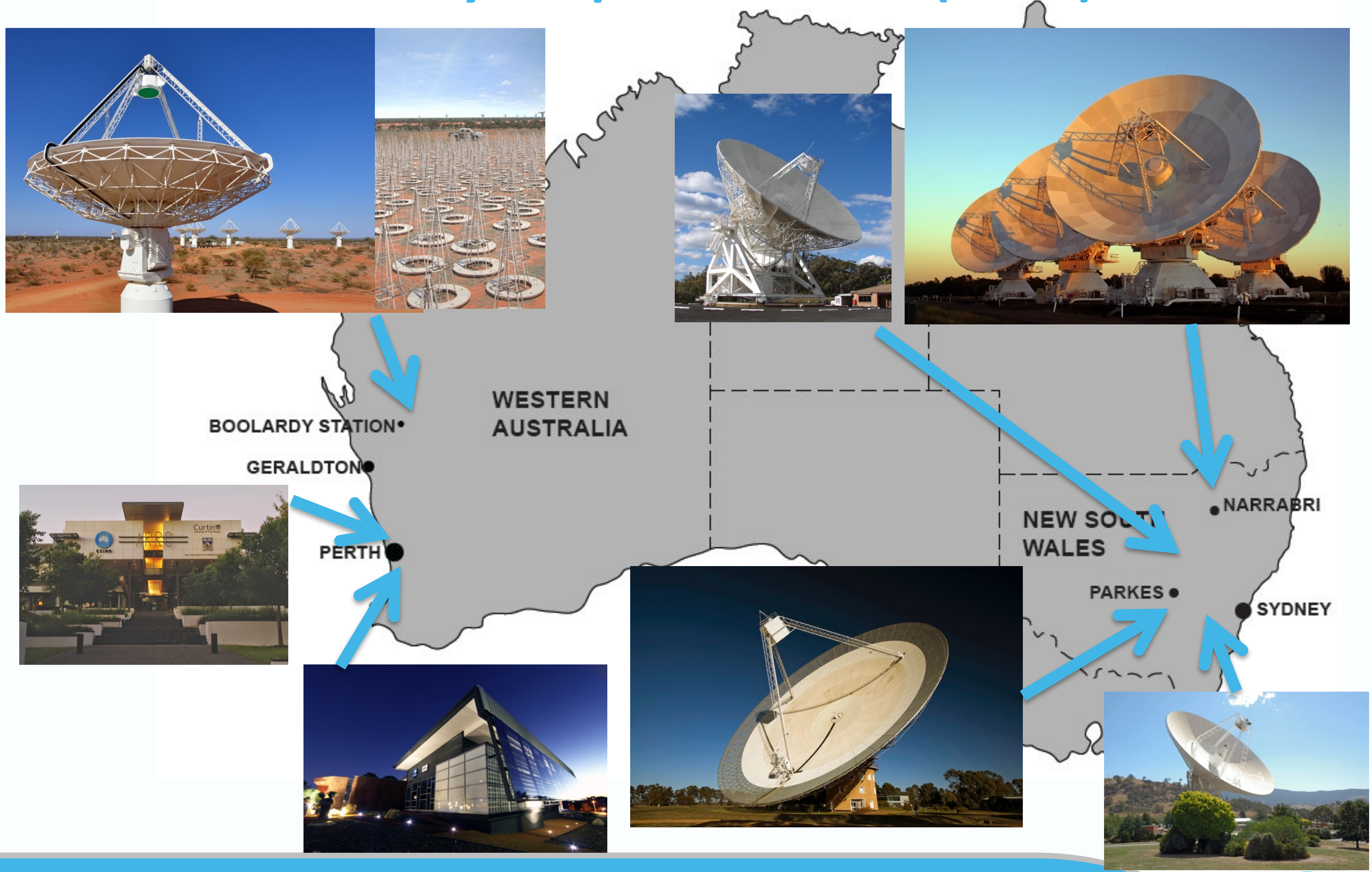
Jan 2018, Kashima, Japan

CSIRO Astronomy & Space Science (CASS)



Parkes

Built in 1960s … still a cutting-edge telescope

Has discovered >1/2 of the known pulsars

Has discovered the first and >1/2 of the known fast radio bursts

Found the double pulsar system

First pulsar timing array project to search for ultra-low-frequency gravitational waves

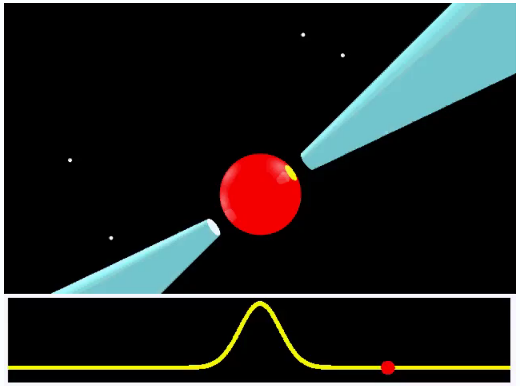
About to be upgraded with a new receiver system. Data sets publically available online (data.csiro.au)

Introduction

1. Overview of pulsar research
2. Searching for pulsars and transients
3. Studying known pulsars
4. What next at Parkes and towards the SKA?

Pulsar research

1. Studying the neutron star structure, emission and population
2. Using the pulsars as tools to study “extreme” physics:
   - The interstellar medium
   - The solar corona
   - Relativistic astrophysics
   – Gravitational waves
   – Tests of General Relativity
3. Using pulsars for practical applications:
   - Aid in improving solar system ephemerides
   - Aid in improving terrestrial time standards
   - Navigation applications



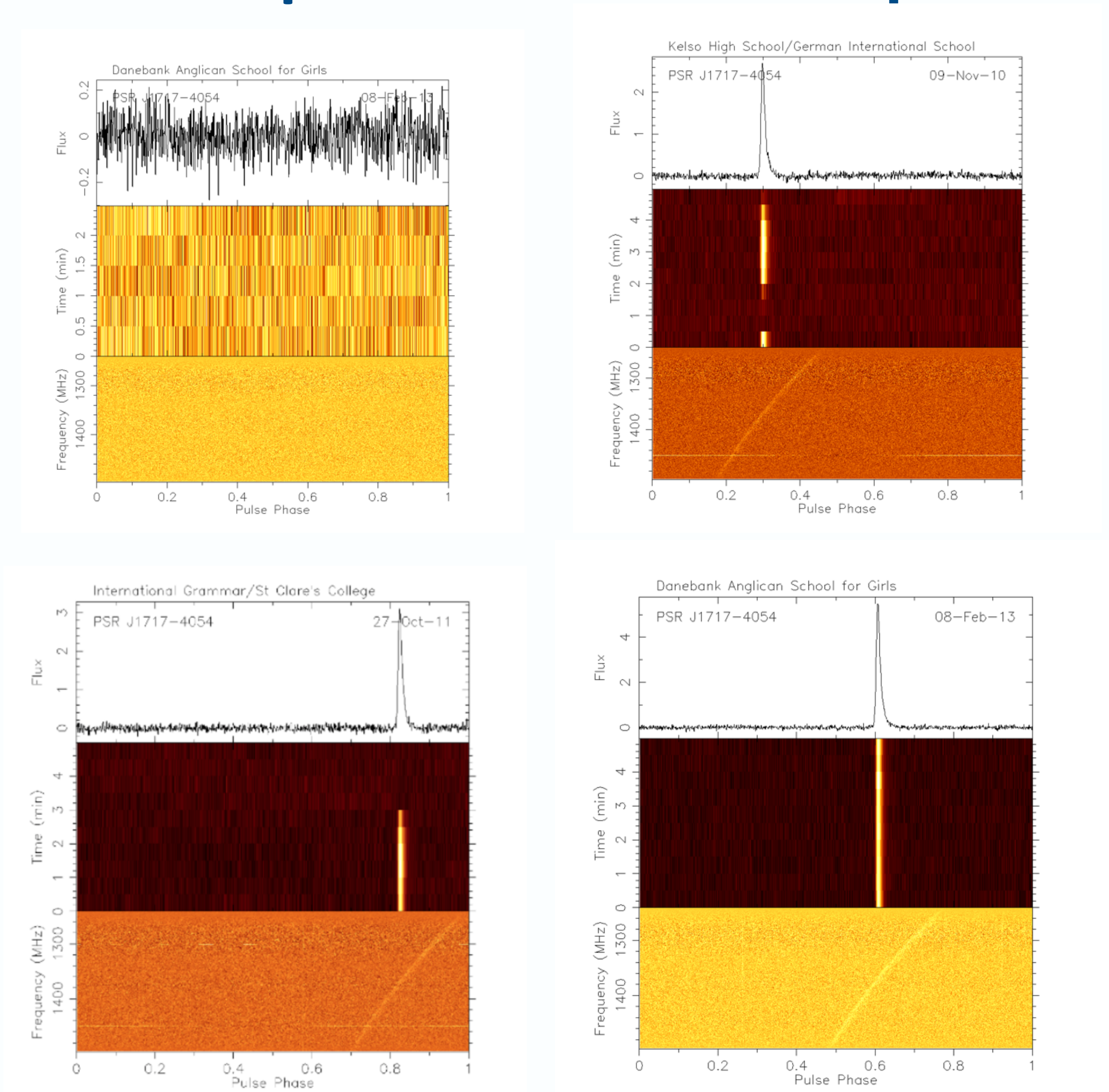
Diameter: ~20km
Mass: ~1.4 solar masses
Density ~ 10^{17} kg.m^{-3}
Magnetic field ~10^8 T

Rotational period 1ms < P < 10s

Some un-solved problems: science

1. “What is the maximum mass for a neutron star?” “
2. “why do pulsars glitch?”
3. “what is the pulsar emission geometry and mechanism?”,
4. “why are some pulsars intermittent?”
5. “what is the amplitude of the ultra-low-frequency gravitational wave background?”
6. “what is maximum and minimum pulse period for pulsars?”
7. “what is the relationship between nulling, moding, intermittency, sub-pulse drifting, state-changing?”
8. “do ultra-relativistic orbital systems follow the predictions of general relativity?”
9. “what are the progenitors of fast radio bursts?”
10. …

One example: an intermittent pulsar: PSR J1717-4054



Sometimes it is “on”

Sometimes it is “off”

Sometime it switches back and forth

What is the underlying physical process?

How to tackle such questions?

1. Find lots of new pulsars (and understand the selection effects)
   - Study the general pulsar population in our Galaxy, the Magellanic Clouds, and (with FAST) M31.
   - Find pulsars close to Sgr A* - supermassive black hole at the centre of our Galaxy
   - Find highly-relativistic binary systems
   - Understand the minimum/maximum pulse periods
   - …
2. Monitor the pulsars over decades
   - Measure relativistic effects
   - Detect relativistic phenomena in orbital systems
   - Study small-scale structures in the interstellar medium
   - Detect ultra-low-frequency gravitational waves
   - …

Almost all Parkes pulsar data files are available from data.csiro.au

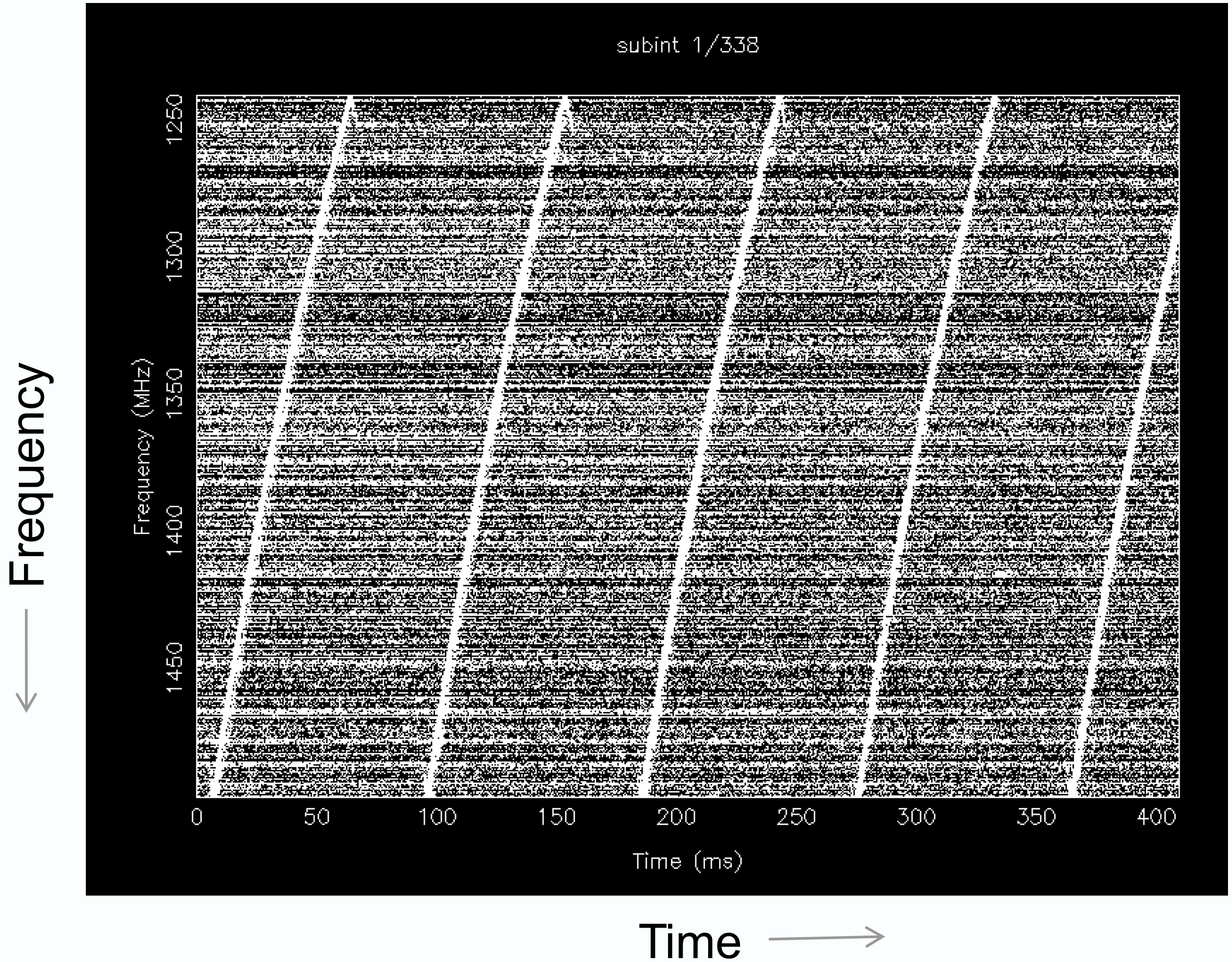
How to tackle such questions?

3. Get a bigger telescope
4. Observe with a wider observing band
5. Go to a more radio-quiet site
6. Observe more often
7. Develop new algorithms that:
    - Increase the parameter space searched (i.e., to shorter or longer pulse periods, to more relativistic binary systems)
    - Are faster => more data can be processed
    - Enable pulsar profile studies over wide bandwidths
    - Improve the modelling of pulse arrival times by accounting for more physical phenomena
    - …

What a pulsar data file looks like

The pulses are dispersed in the interstellar medium

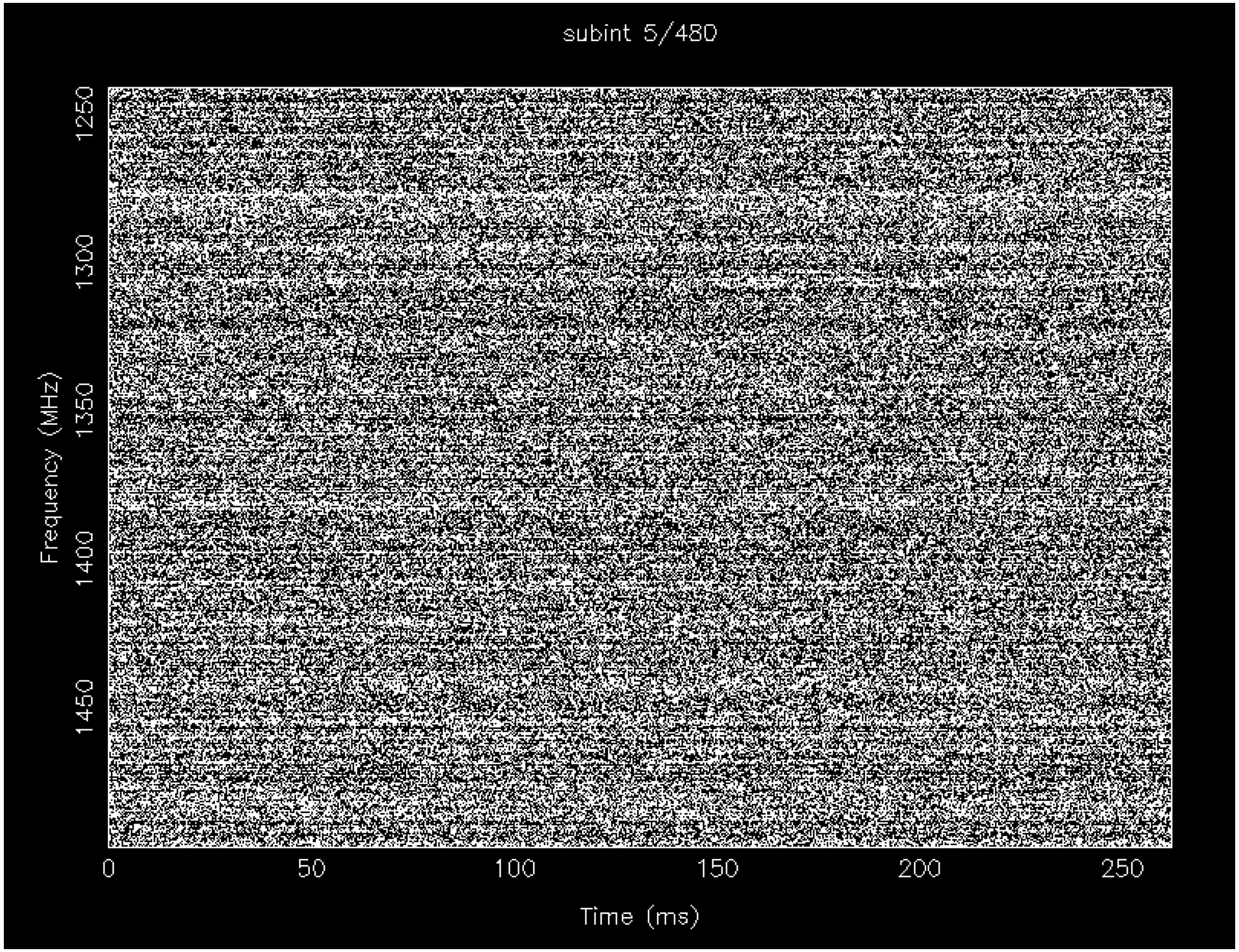
Monitoring changes in the dispersion measure allow us study changes in the interstellar medium on very small scales



1-bit Parkes observations of the Vela pulsar

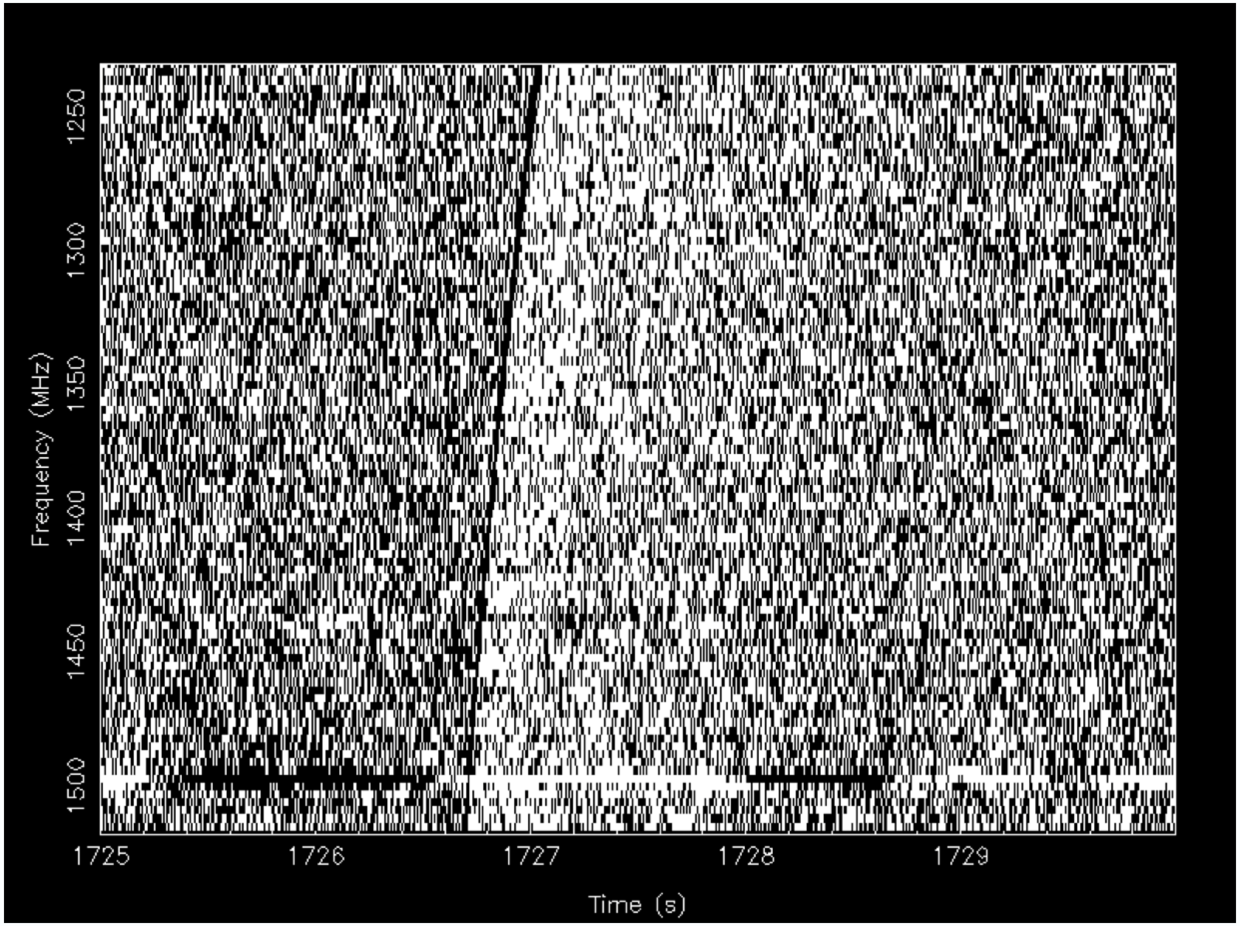
The basics: pulsars are (usually) weak objects

The pulses are somewhere in this plot!



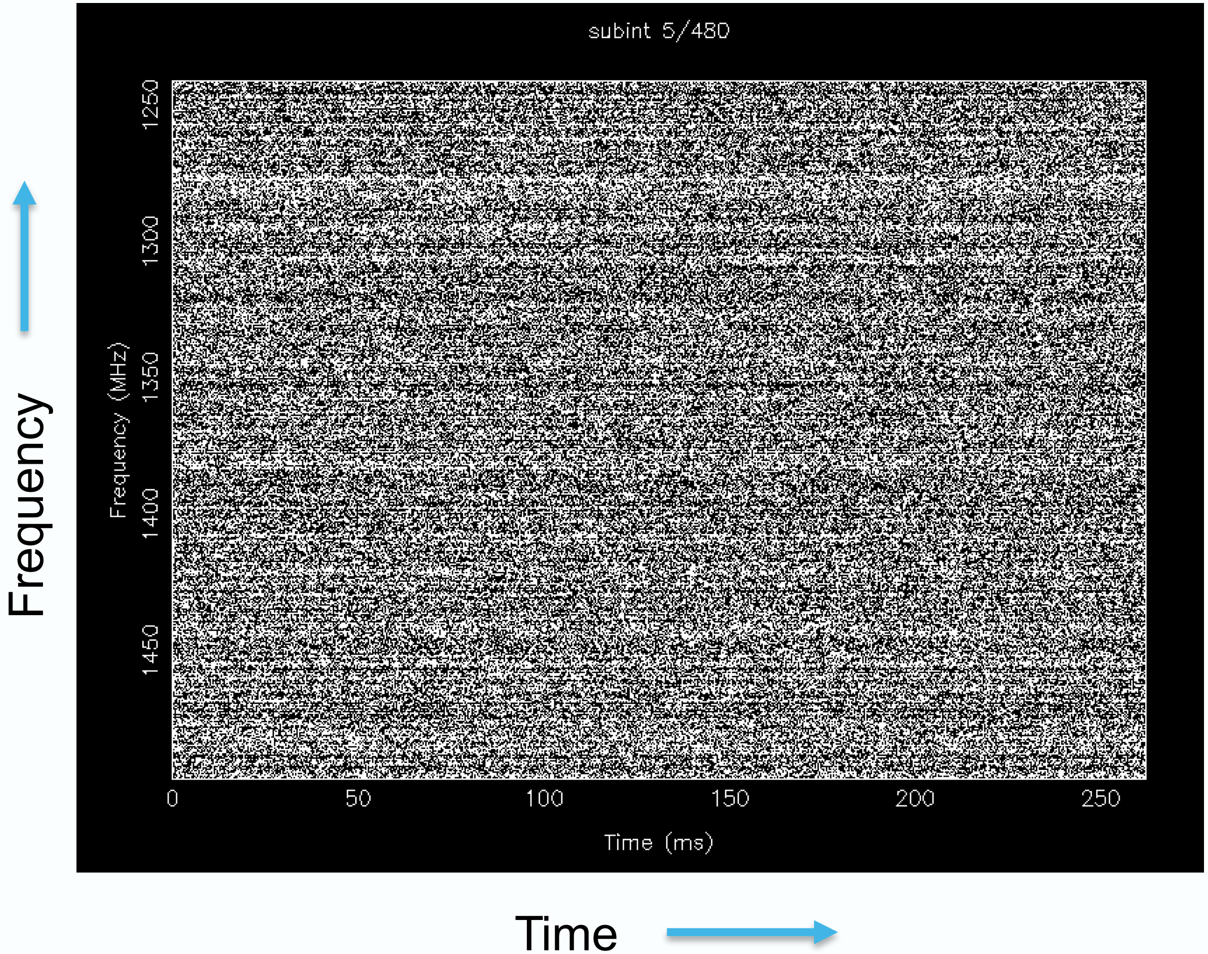
Single pulse searches – fast radio bursts (FRBs)

1. First fast radio burst found in archival Parkes data
2. Single, very-bright dispersed burst
3. The dispersion => not a Galactic object!
4. What are they?

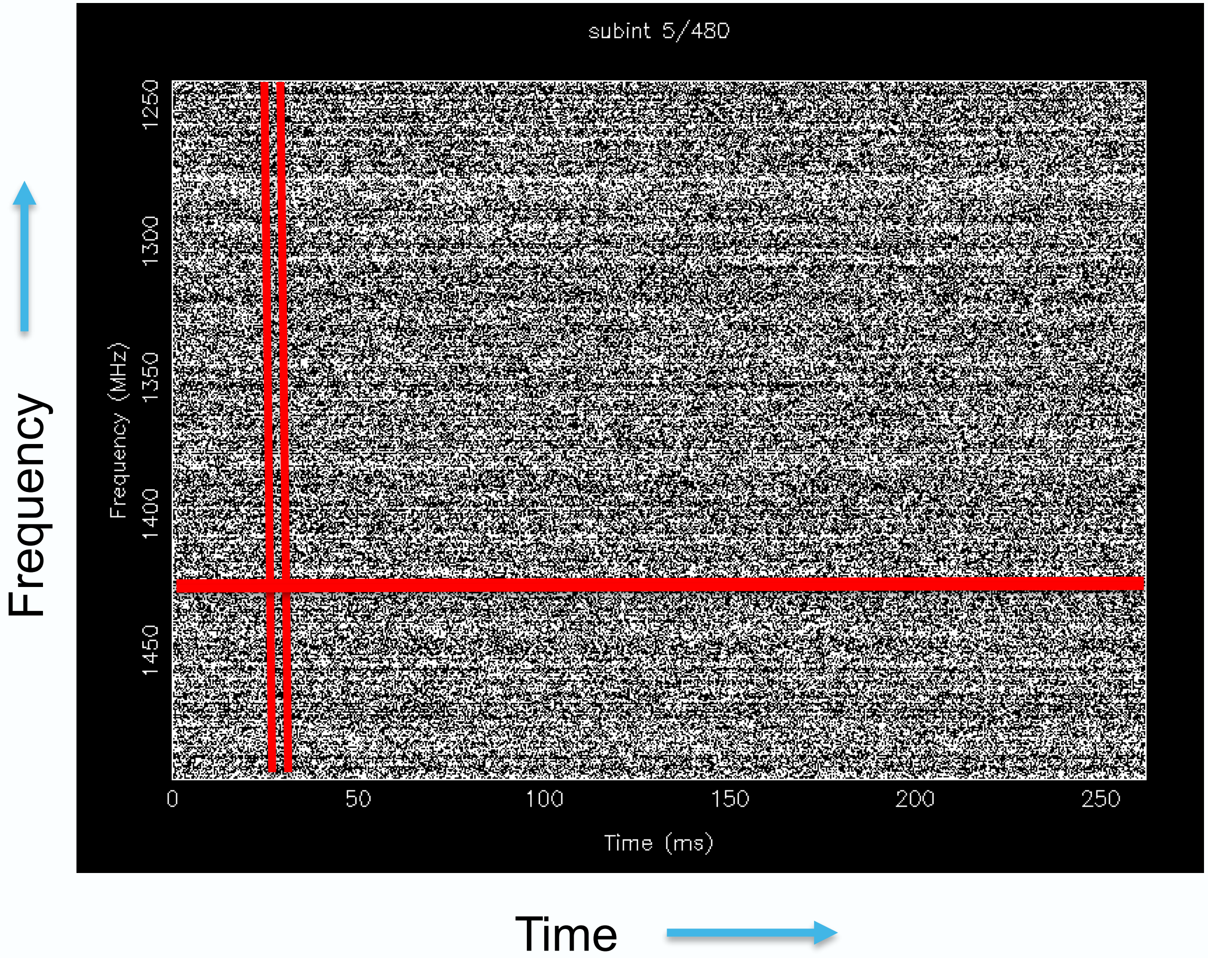


Pulsar search-mode data sets

- Noise

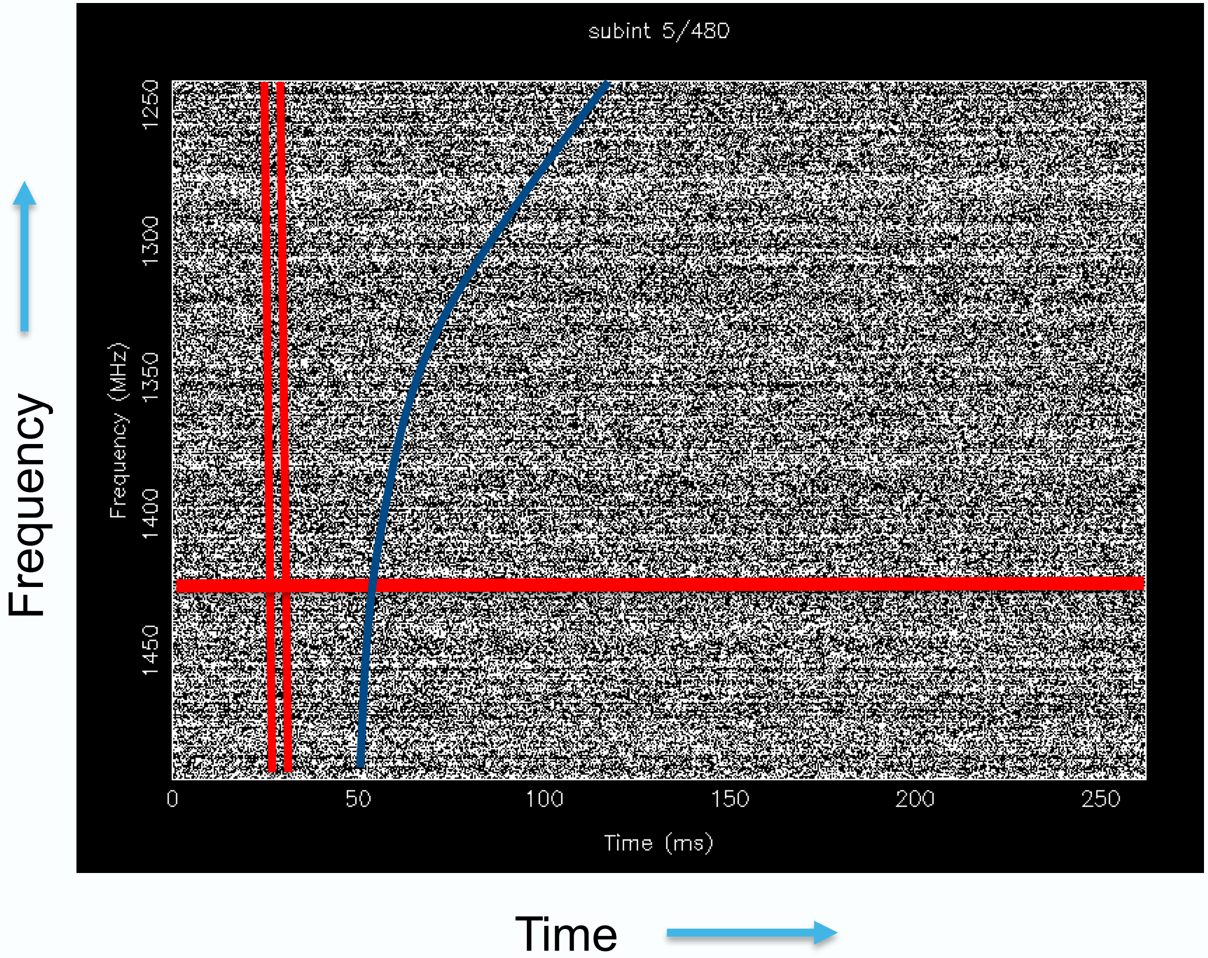


Pulsar search-mode data sets



- Noise
- Impulsive RFI (air conditioners, cameras …)
- Narrow-band RFI (mobiles, aircraft communication …)
- Periodic RFI (e.g., 50 Hz from mains electricity)

Pulsar search-mode data sets



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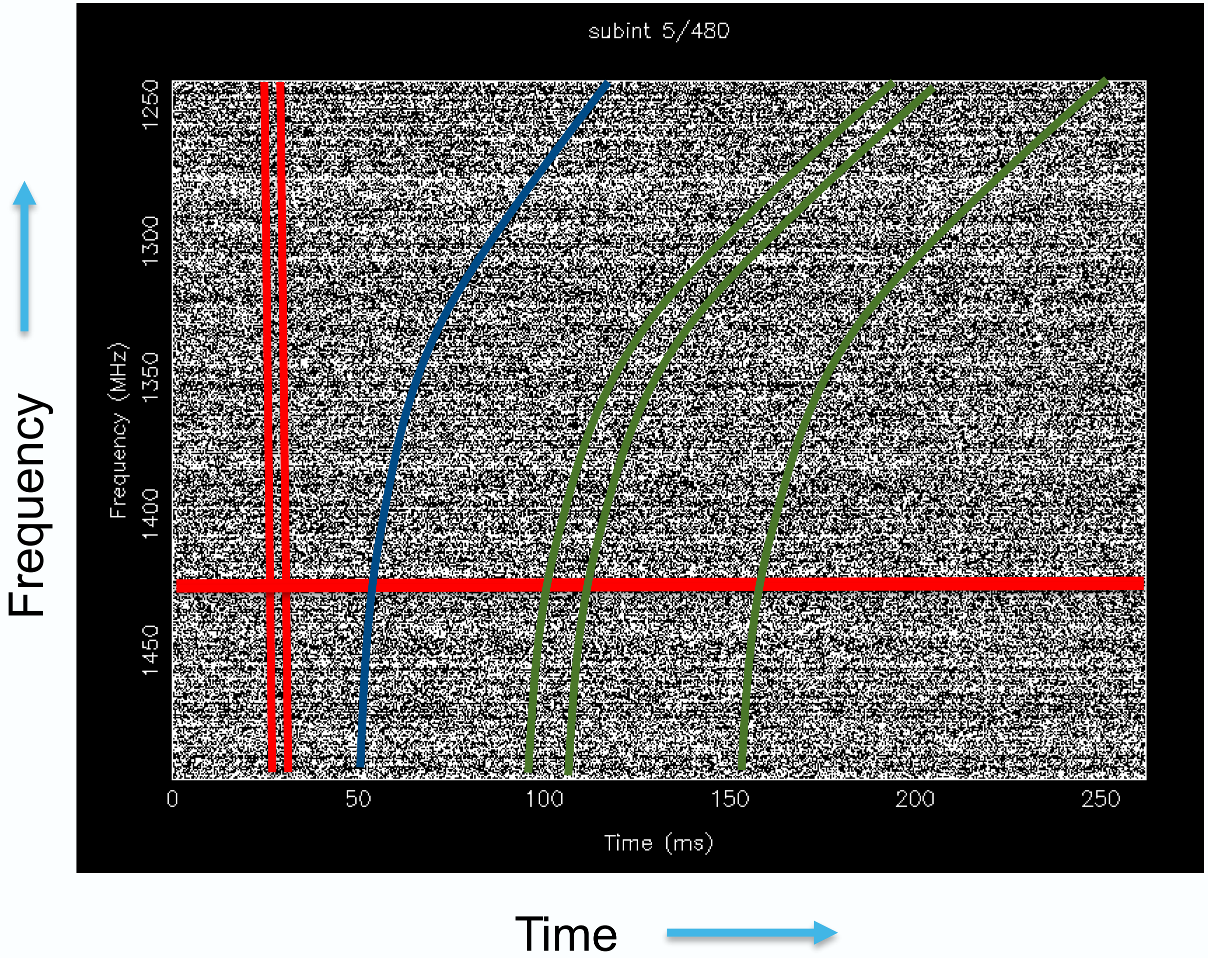

- Noise
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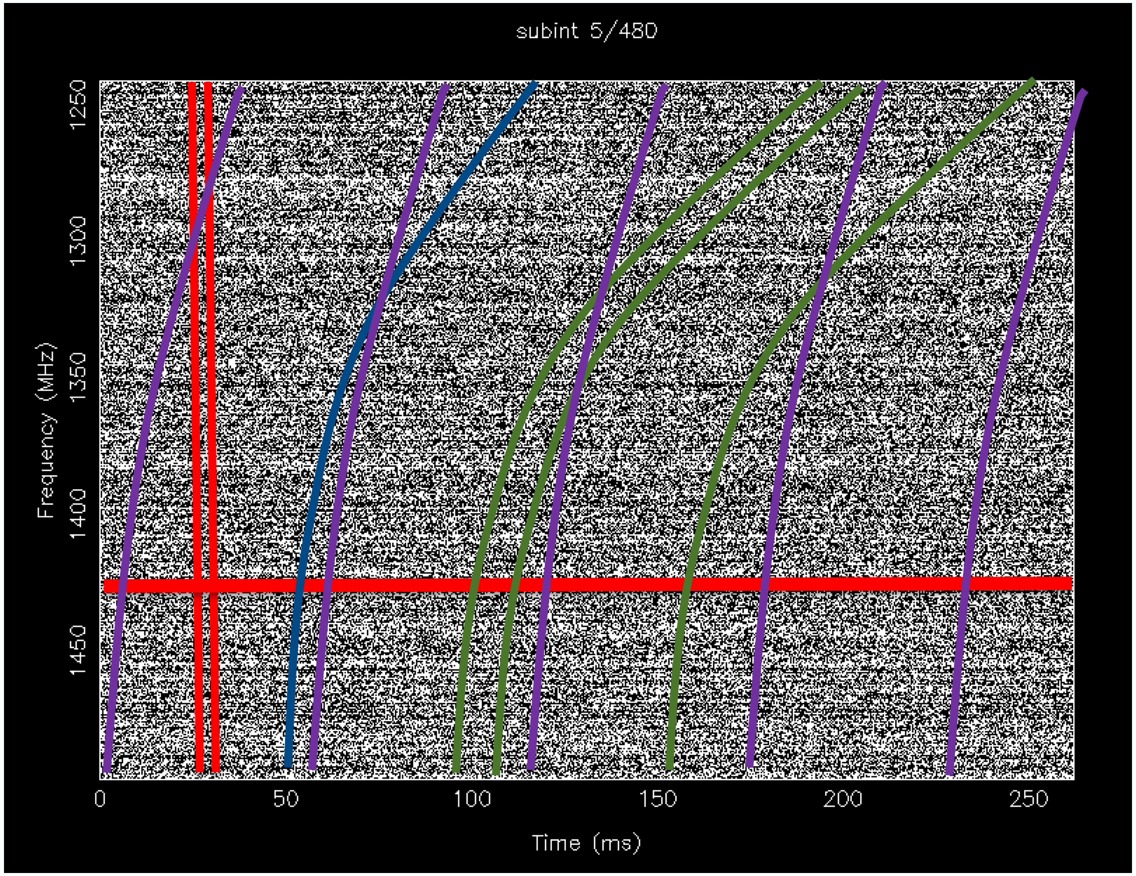
- Fast radio bursts
- RRATs

Pulsar search-mode data sets

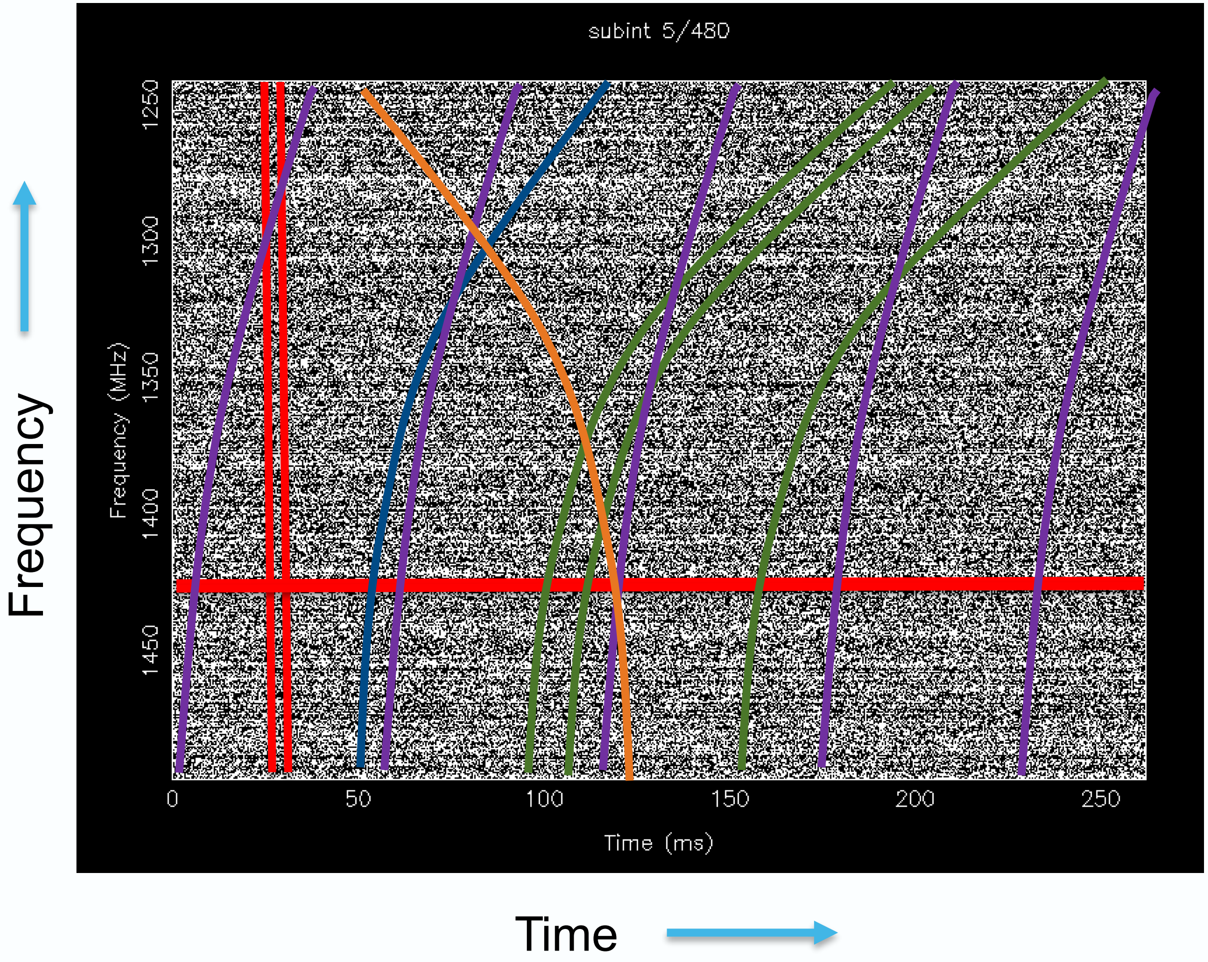


Frequency

Time

- Noise
- Impulsive RFI (air conditioners, cameras …)
- Narrow-band RFI (mobiles, aircraft communication …)
- Periodic RFI (e.g., 50 Hz from mains electricity)
- Fast radio bursts
- RRATs
- Pulsars

Pulsar search-mode data sets



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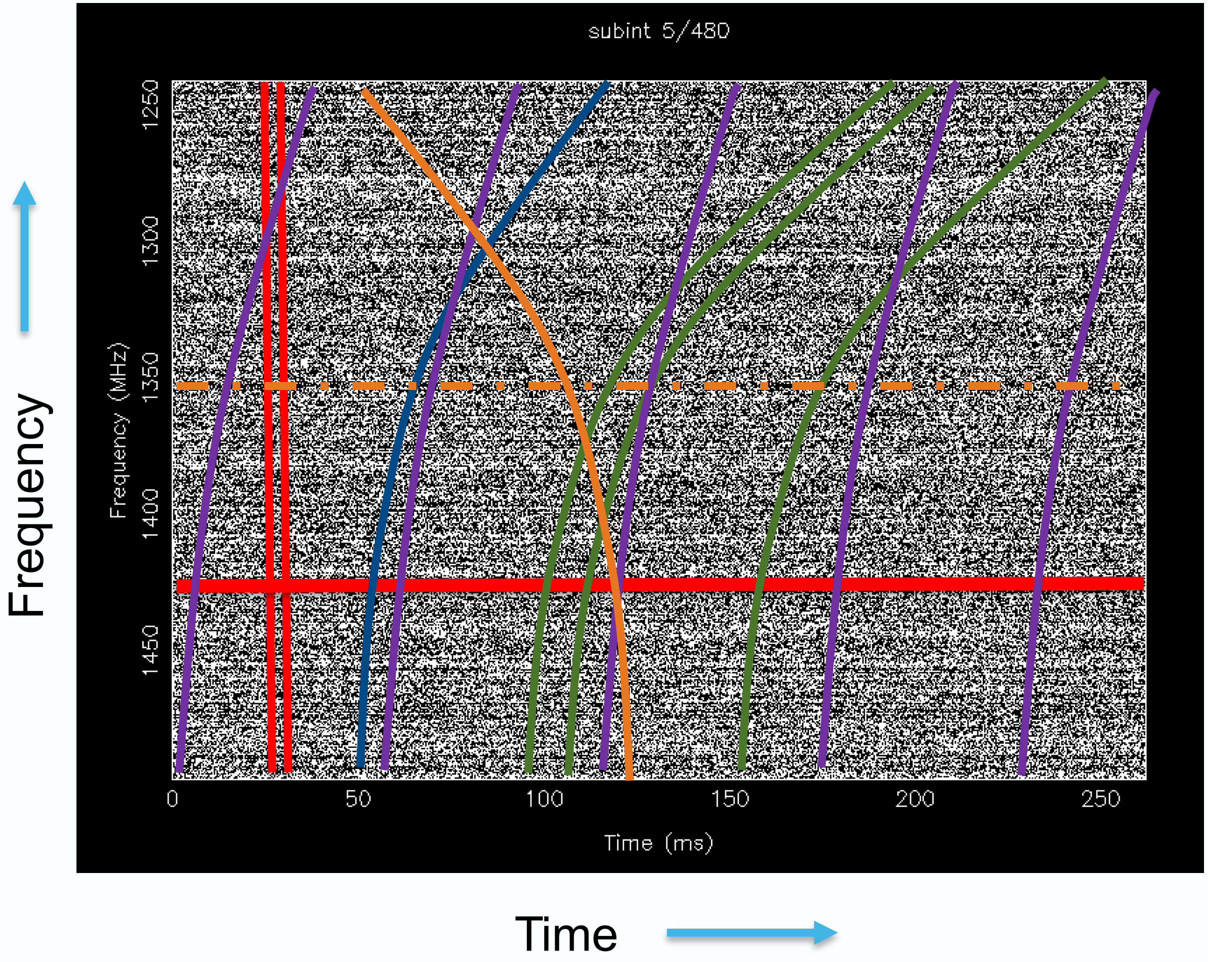
- Fast radio bursts
- RRATs
- Pulsars
- Flare stars ??
- Aliens (SETI)

Pulsar search-mode data sets



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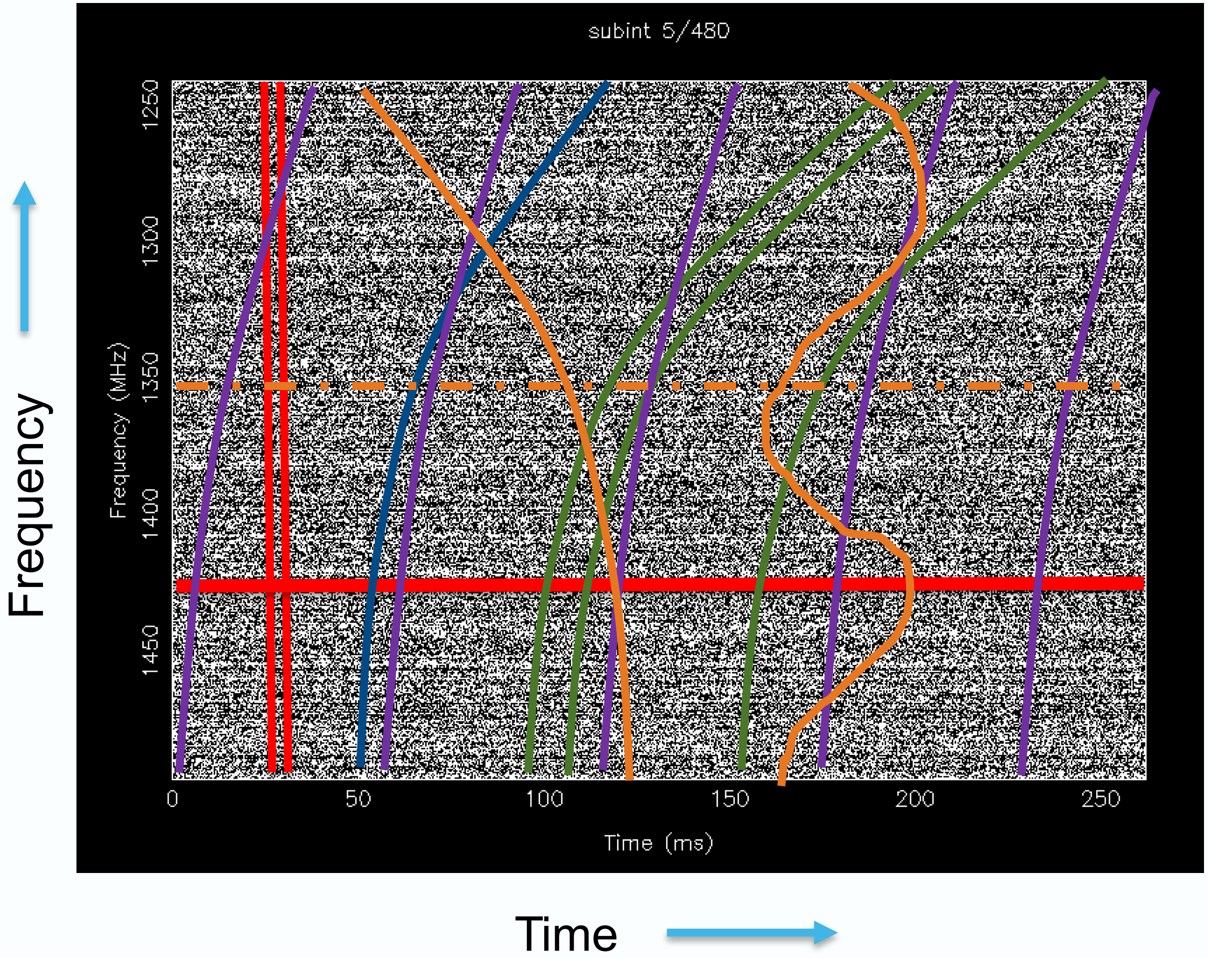
- Aliens (SETI)
- More SETI

Pulsar search-mode data sets



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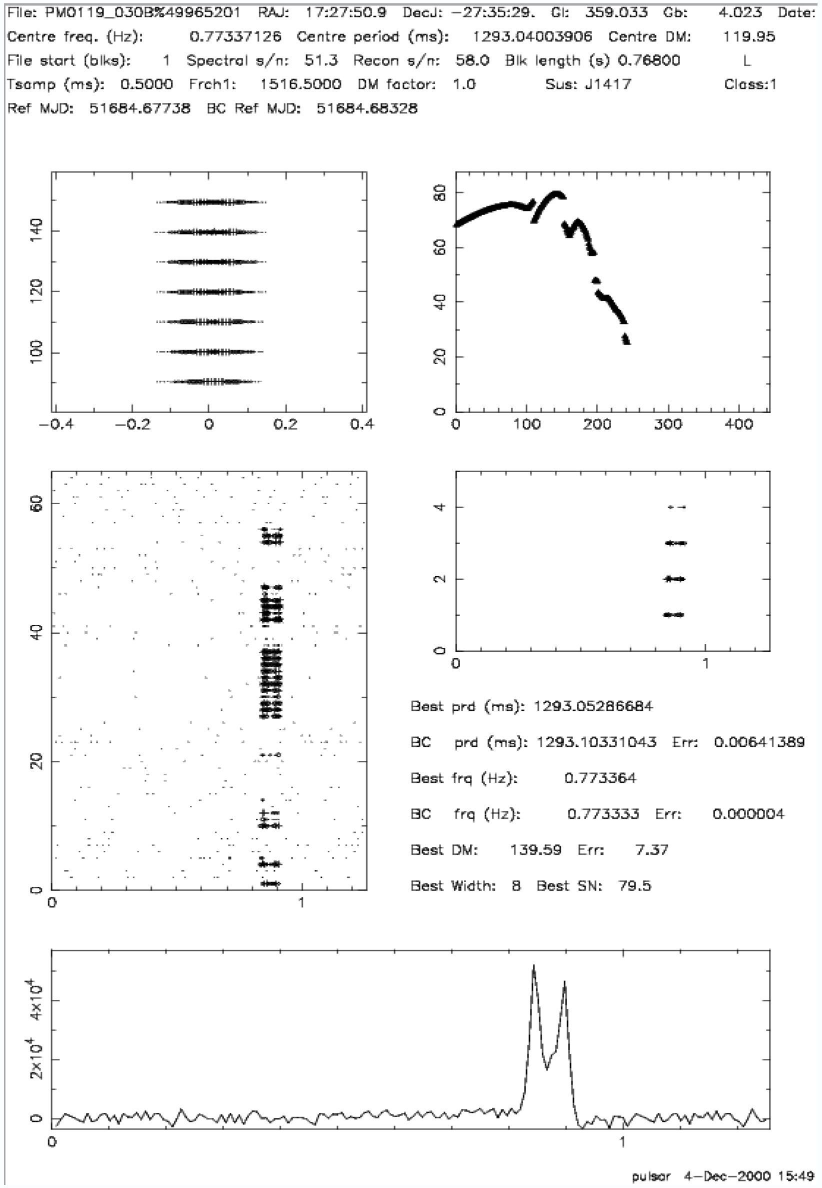
- Aliens (SETI)
- More SETI
- More SETI

Our existing algorithms are excellent at looking for pulsars, but not for aliens

The basic search method

1. Record some data
2. Dedisperse at a range of possible dispersion measures
3. Sum across frequency channels to form a single time series for each dispersion measure
4. Fourier transform each time series
5. (If necessary, relate harmonic features in the power spectrum)
6. Look for periodic signals (pulsar candidates)

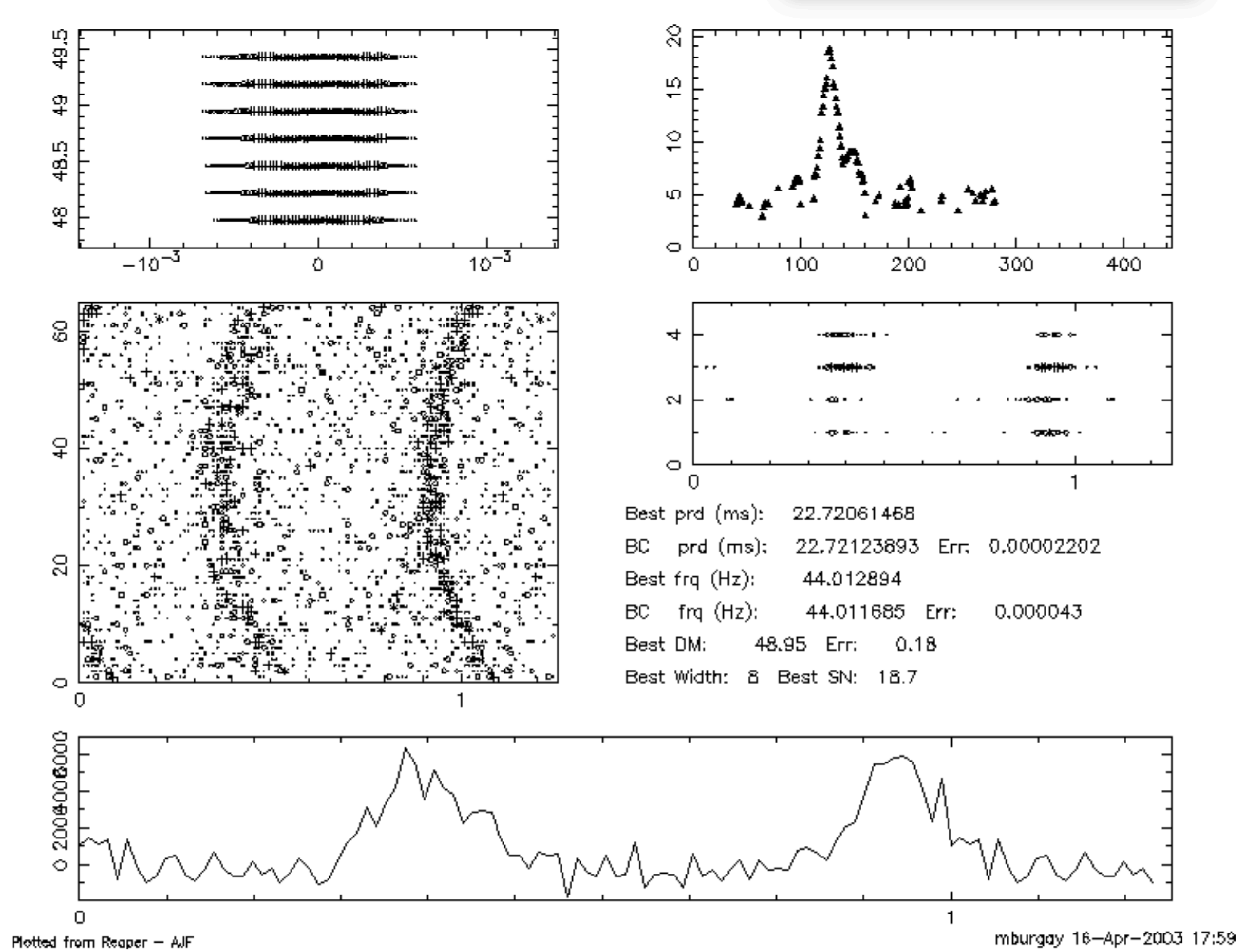


Highlights from Parkes: The double pulsar

Image from Marta Burgay

"pulsar B was not discovered in the survey because it was not on in those 4 minutes"

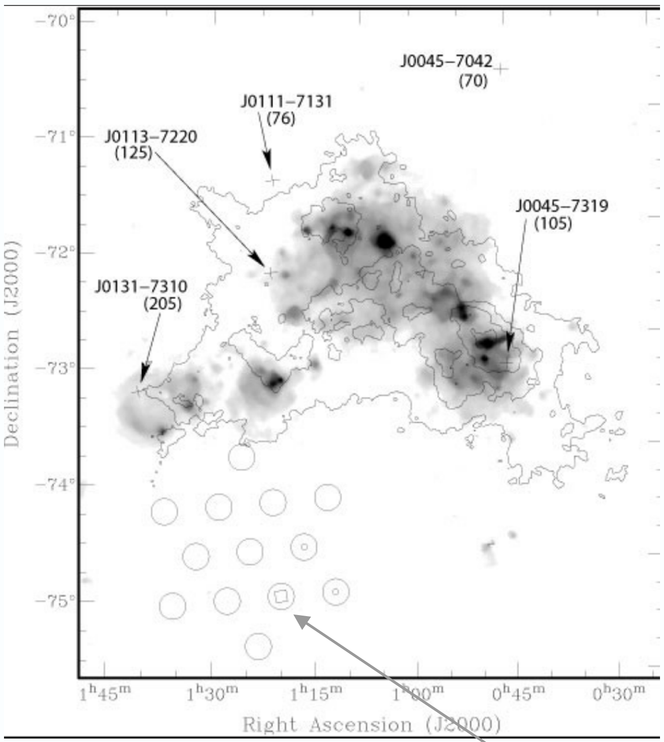
The "B" pulsar was discovered in subsequent observations



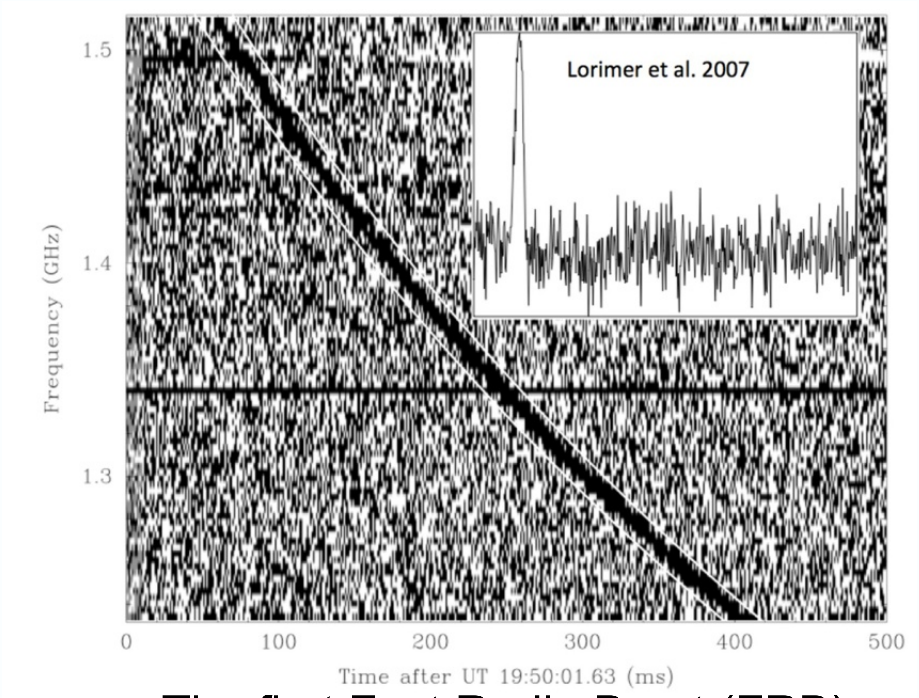
Data was easily accessible to trial new algorithms
Look at data.csiro.au. Perhaps more pulsars hiding in existing data!

FRBs

Duncan Lorimer processed an accidental pointing in the Magellanic Cloud survey and ….



The pointing



The first Fast Radio Burst (FRB)

Data was easily accessible to trial new algorithms

(Just an aside)

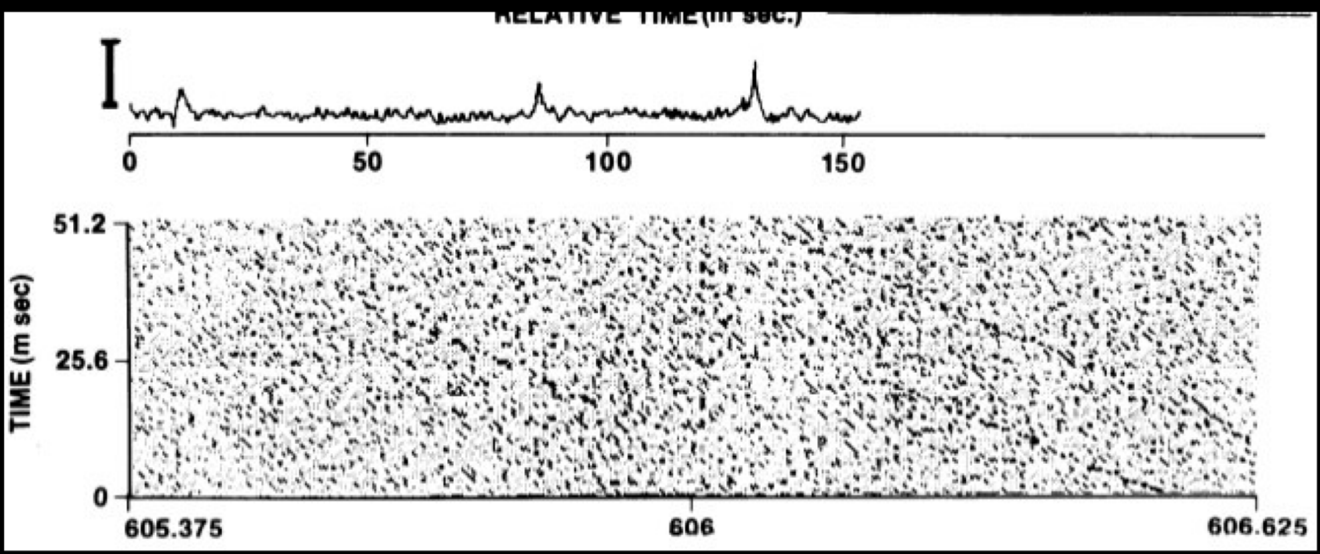
1979

DISCOVERY OF MILLISECOND RADIO BURSTS FROM M87

I. R. Linscott and J. W. Erkes[1]
Dudley Observatory, Schenectady, New York
Received 1979 August 10; accepted 1979 December 19

ABSTRACT

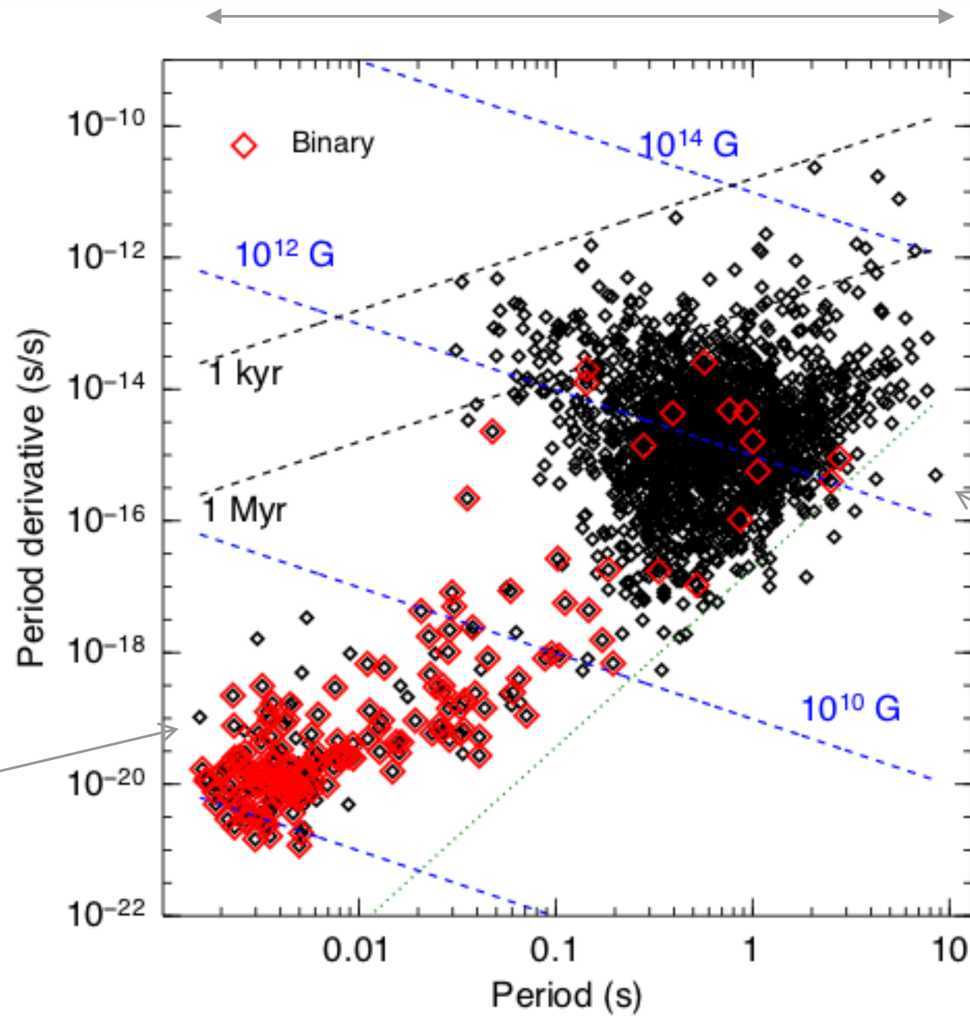
Highly dispersed radio pulses have been detected from M87 at radio frequencies of 430, 606, and 1420 MHz. The pulse sweep rates scale with the third power of the observing frequency as expected from the cold plasma law. The sweep rates correspond to dispersion measures in the range $1-5 \times 10^3$ parsec cm^{-3}. The pulses frequently appear grouped together separated within the group by approximately 50 ms. Peak power levels of 100 Jy and temporal widths of a few ms for individual pulses are found, and the group repetition rate is of the order of $1\ s^{-1}$.



Slide from D. Lorimer

"… according to Joe Taylor, they were most likely traced to instrumental glitches on an old AO FFT spectrometer"

The pulsar population now

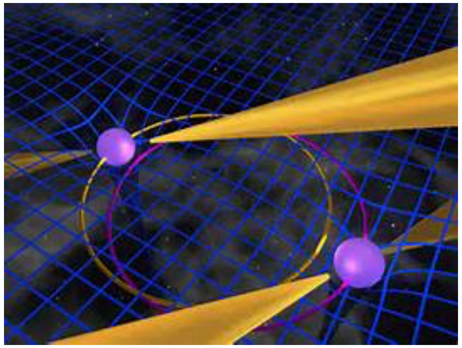


Edges likely to be caused (partially) by selection effects

Very long period (~10s) pulsars

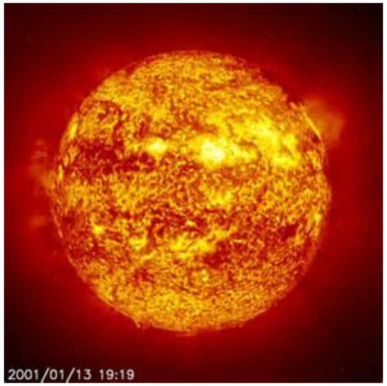
Lots of millisecond pulsars

Pulsar timing

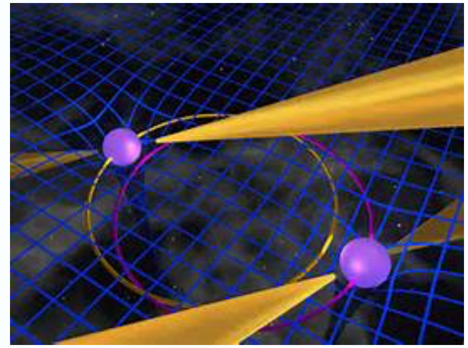


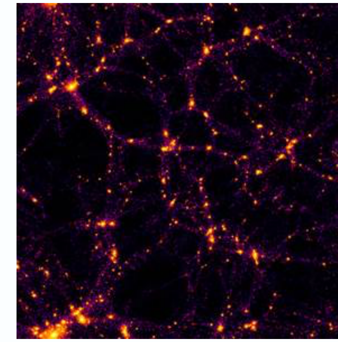
Counselman & Shapiro (**1968**)

"pulsars … can be used to test general relativity, to study the solar corona, and to determine the earth's orbit and ephemeris time … and the average interstellar electron density."

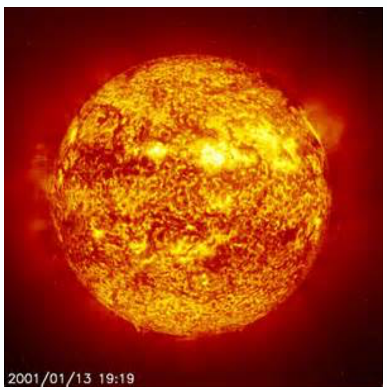


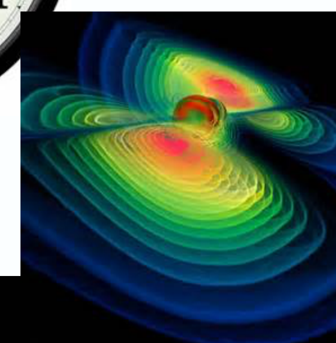
Pulsar timing





Now also …
- searching for dark matter clumps
- searching for gravitational waves
- studying extra-solar planets
- probing the interior of neutron stars …

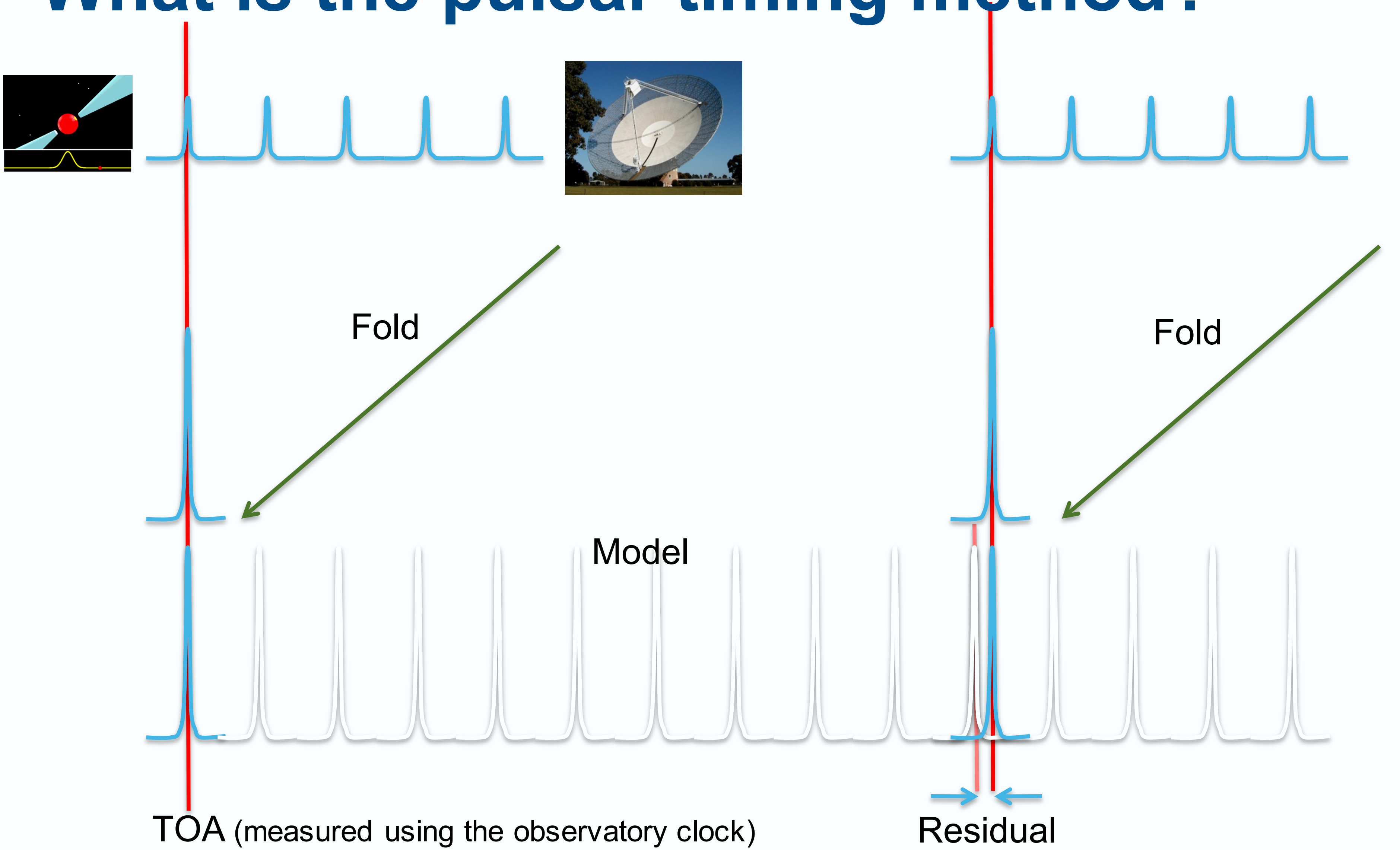




The pulsar timing method!

Slide from D. Champion

What is the pulsar timing method?

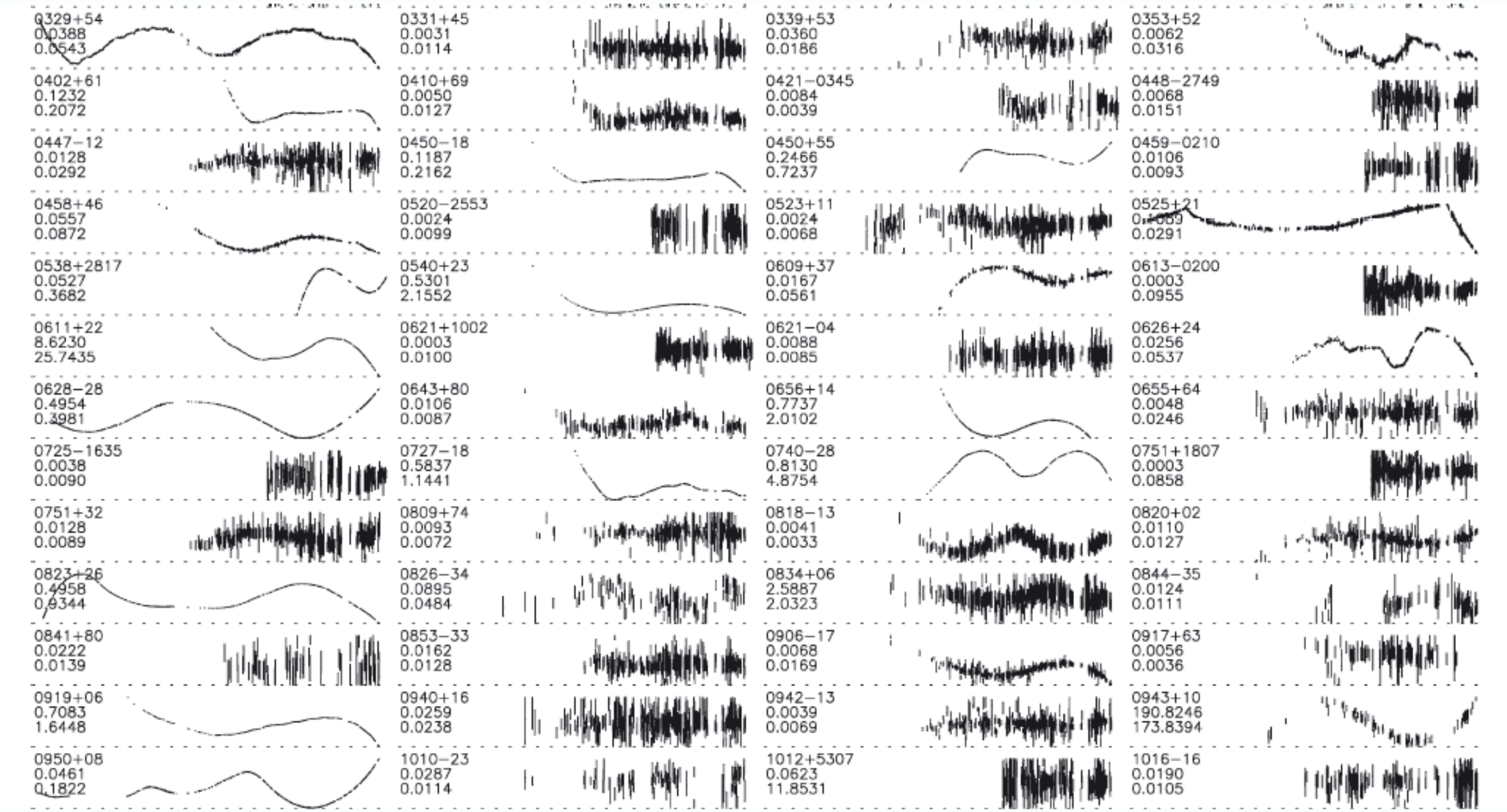


The tempo2 software package

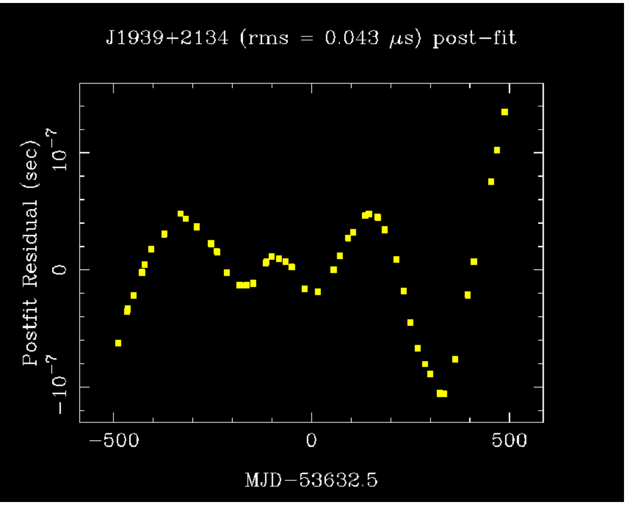
1. Loads in measured pulse arrival times and a simple model for the pulsar (position, pulse period, dispersion measure, etc.)
2. Predicts the expected pulse arrival times (known physics modelled to the 1ns level) based on the model.
3. Forms pre-fit timing residuals that are the difference between the predictions and the observations
4. Iteratively (using frequentist of Bayesian methods) improves the model
5. Forms post-fit timing residuals using predictions from the updated model

If the model is “good” then the timing residuals will be consistent with zero (i.e., the pulse arrival times can be predicted by the model)

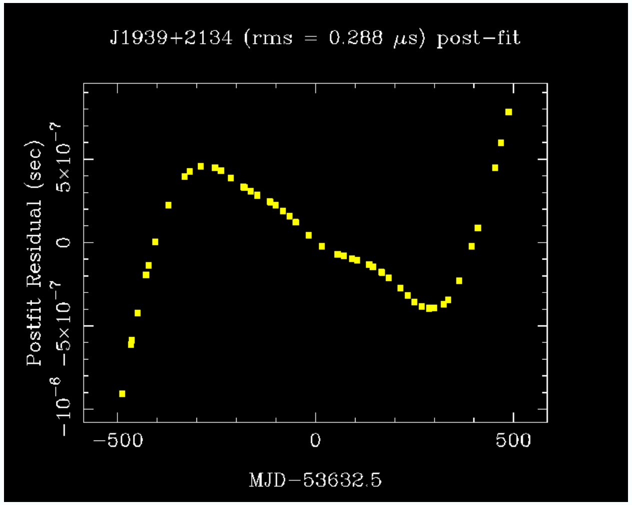
Some timing residuals



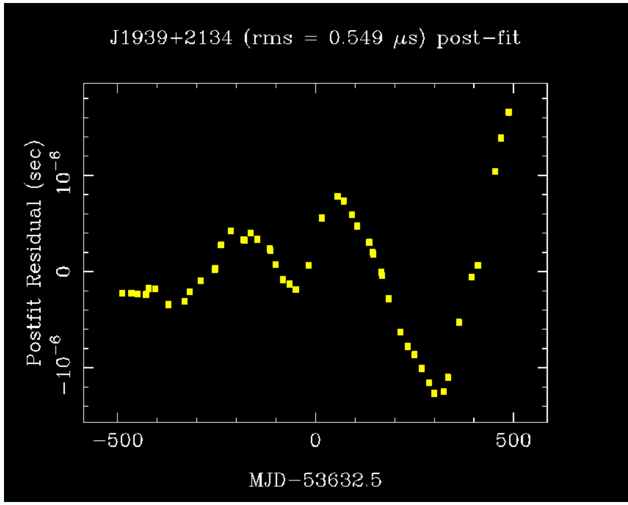
Pulsar Timing Array research: looking for correlations



GW background



Spin-down irregularities

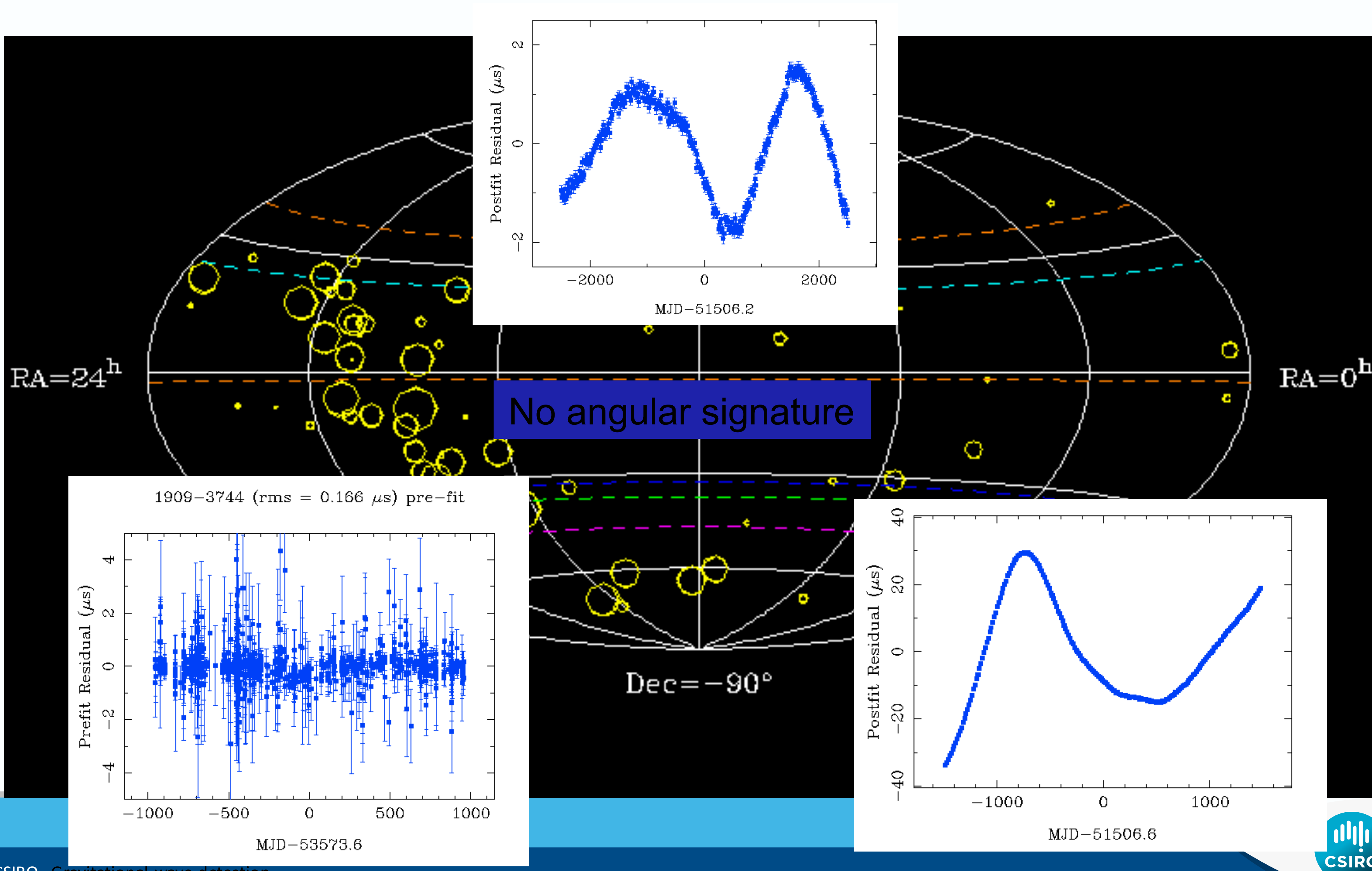


Clock noise

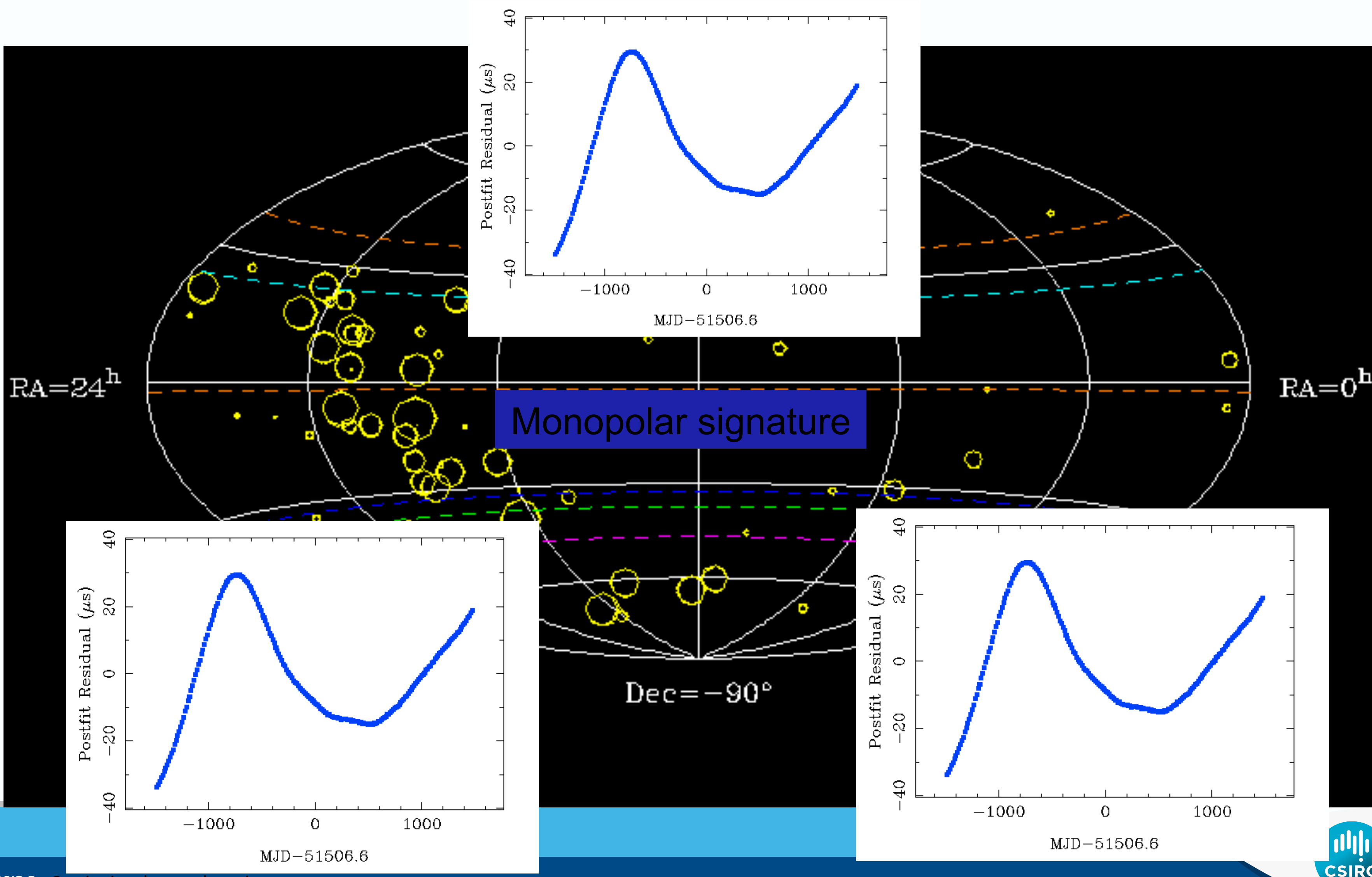
With one pulsar you cannot (normally) tell what unmodelled physical effect is causing the residuals

Simulated data

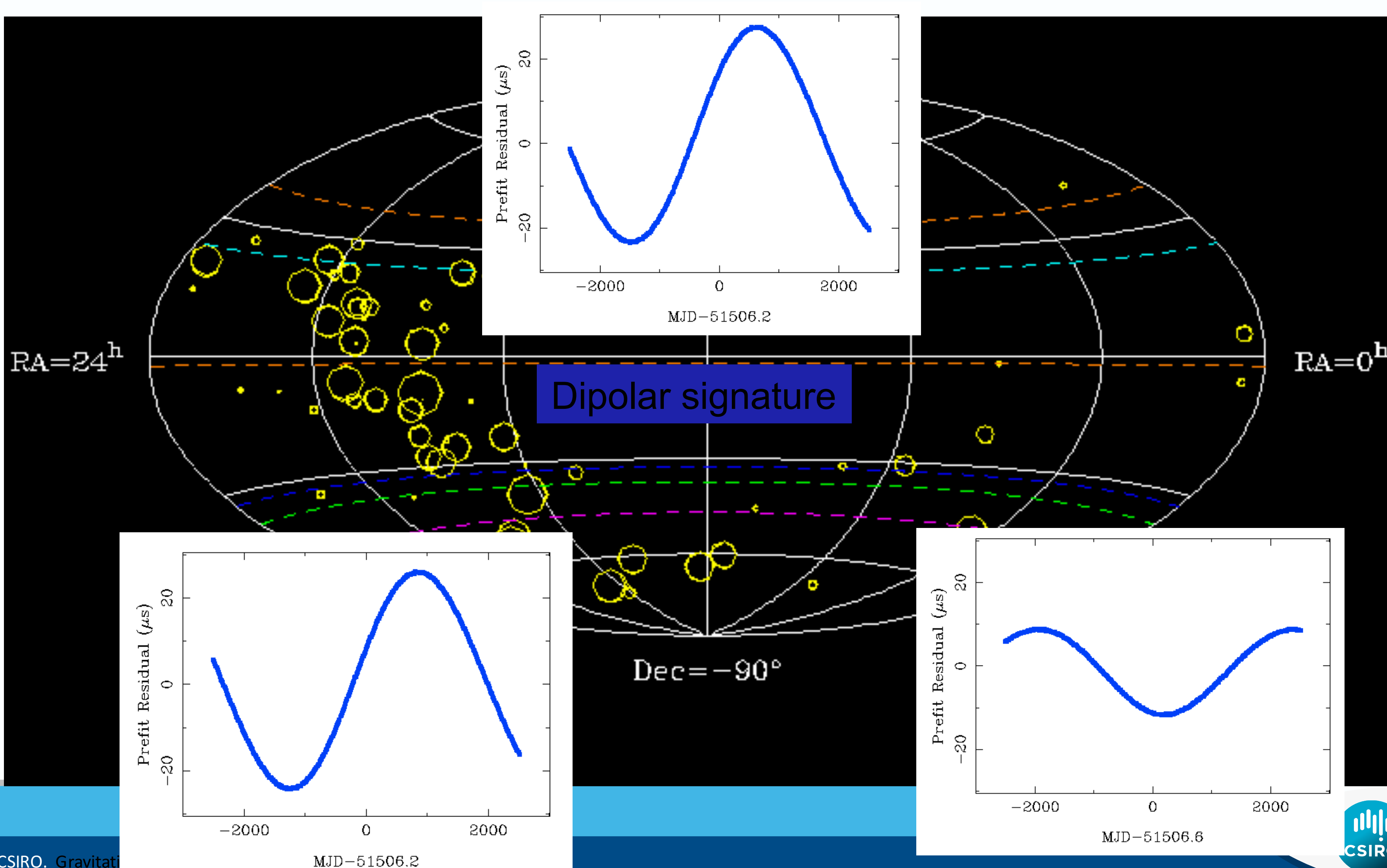
Spin-down irregularities



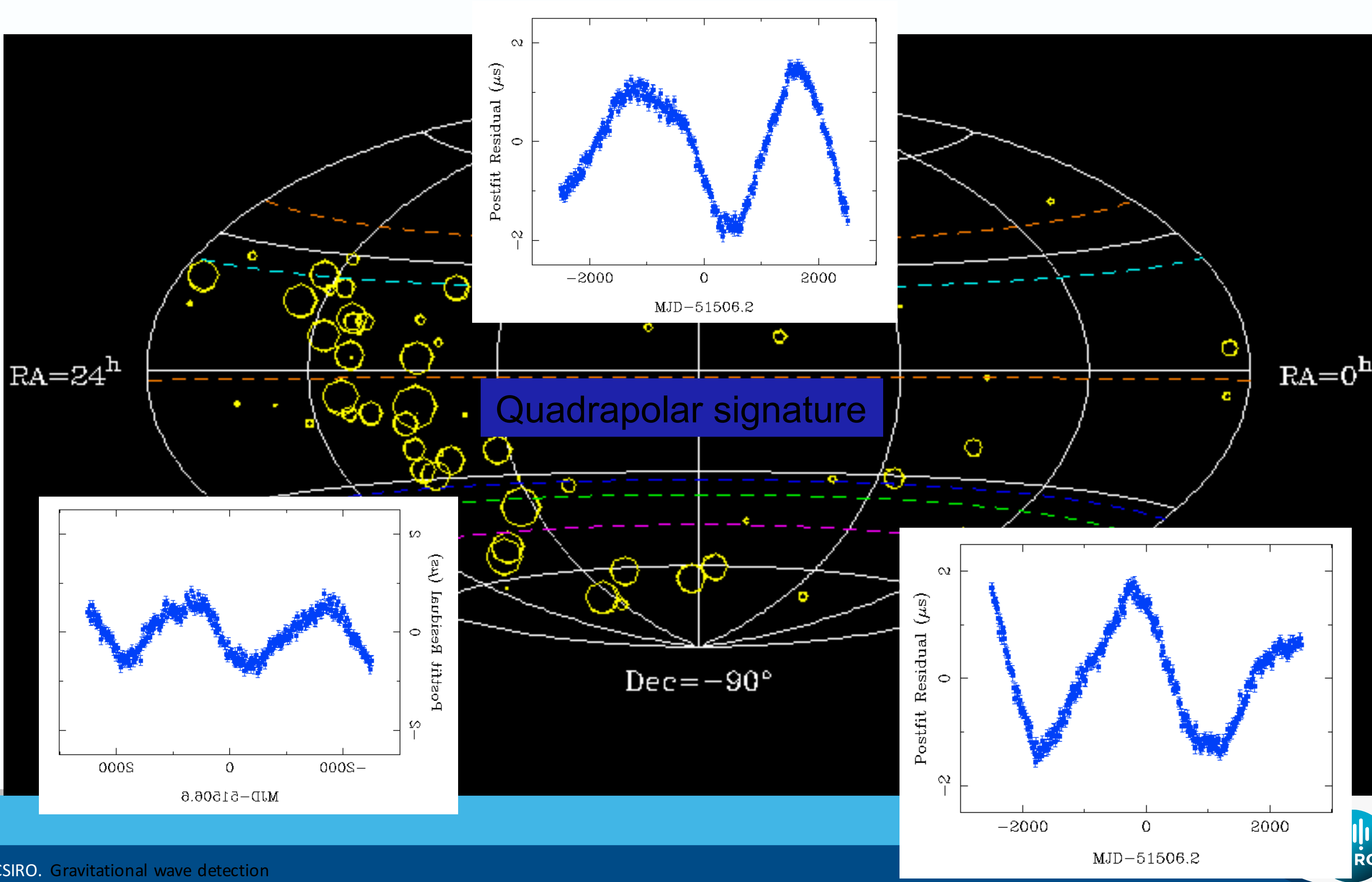
Terrestrial time standard irregularities



Errors in the planetary ephemerides - e.g. error in the mass of Jupiter

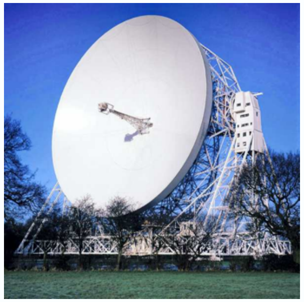


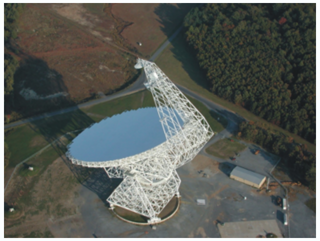
What if gravitational waves exist?



The Parkes Pulsar Timing Array project

International Pulsar Timing Array





NANOGrav

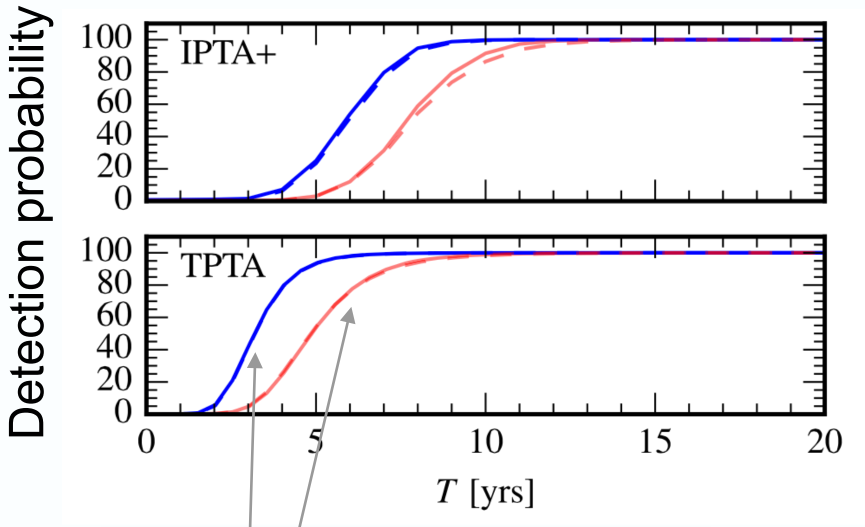
PPTA

EPTA

CSIRO

When will we detect gravitational waves?

Some people are optimistic (Taylor et al. 2016)



Different stalling models

Some people are pessimistic:

"will take >40 years"

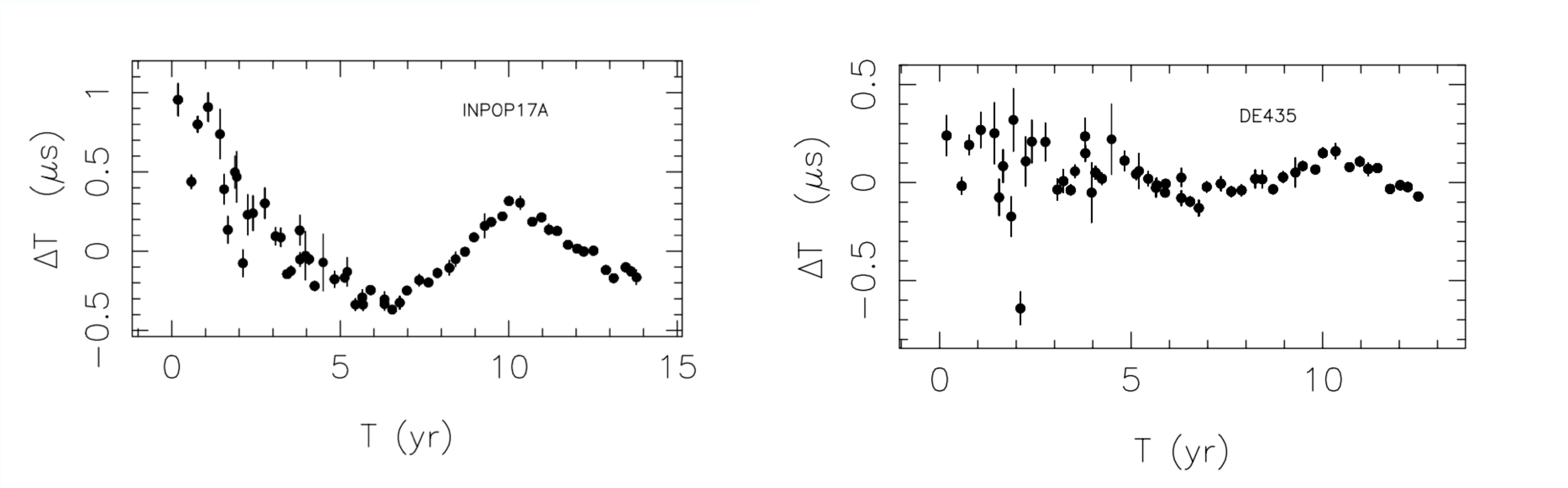
"need to change our observing strategy"

"the last parsec problem may imply that black hole binaries do not coalesce => no signal"

…

Active area of research

Our current "biggest" problem: The solar system ephemeris



- The observed residuals depend upon the choice of solar system ephemeris.
- Something is wrong either with the solar system ephemerides or with our way of processing the data.
- Very active area of research, but still un-solved.

Other outstanding problems relating to studies of known pulsars

1. Bayesian codes very slow.
2. How can we predict (and measure) pulse arrival times over a wide-bandwidth?
3. Some orbital systems are very complex (3-body orbits) and not well modelled
4. What is the optimal method to mitigate errors in time standards, solar system ephemerides without losing sensitivity to gravitational wave signals?

10 year guess

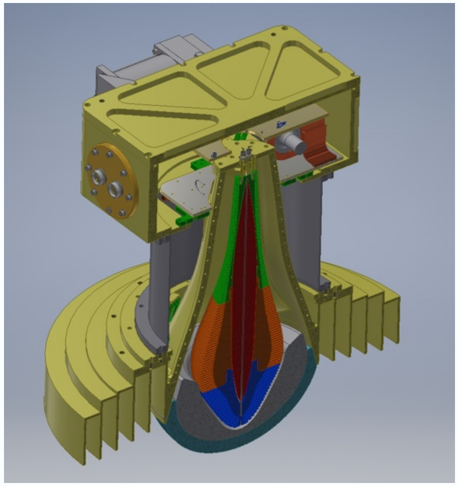
1. Detected (or evidence for) a gravitational wave background
2. Timing models that can deal with multiple orbiting bodies
3. Wide-band timing methodologies
4. Better understanding of small-scale structures in the ISM
5. Better understanding of the relationship between the radio emission and the high-energy emission for transitional/moding pulsars
6. Improved solar system ephemeris (from timing and VLBI)
7. Data processing will occur in the Cloud.
8. …

How will we get there? … new instrumentation

Wide-band receiver

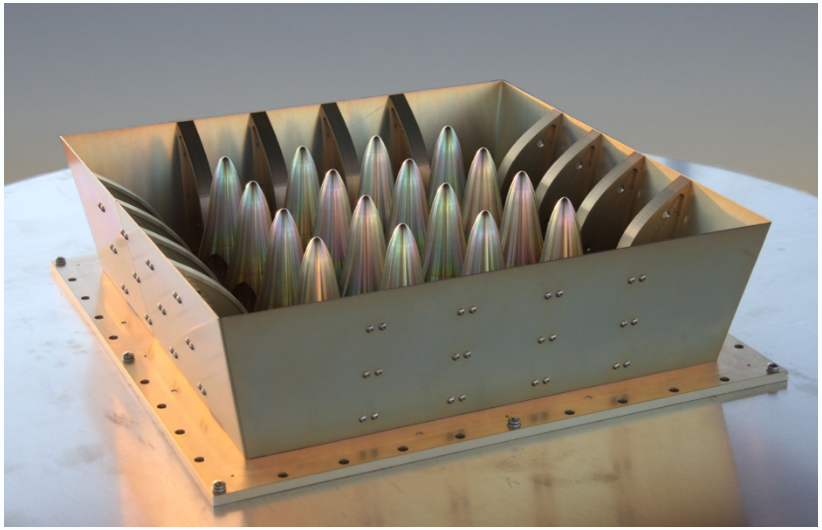
- 704-4032MHz -26x128MHz
- ~20K T_{sys}

Operational March 2018



Cryo-PAF at Parkes

- 0.7 – 2 GHz bandwidth, 36 beams
- 3 x FoV of MB20
- T_{sys} < 20K
- Expected on telescope ~2020



How will we get there? … new telescopes

Square Kilometre Array (in the Southern Hemisphere) and FAST (in the Northern hemisphere) will revolutionise pulsar astronomy

- Detect the majority of the pulsars in our Galaxy
- Discover large populations of pulsars in other Galaxies
- Detect a huge number of Fast Radio Bursts
- Study pulsars from very low frequencies to very high frequencies
- …

Thinking about the SKA

1. Most pulsar discoveries and observations have been carried out with a single dish telescope (Jodrell, Effelsberg, Parkes, Arecibo, GreenBank …). Lots of questions around discovering and observing pulsars using an interferometer (although Westerbork, GMRT, VLA etc. have observed pulsars)
2. Much pulsar research relies on regular observations of hundreds of pulsars. With the discovery of 10,000+ pulsars how will we monitor them all (or choose which to ignore)?
3. Processing pulsar surveys requires high performance computers. Can we process SKA data sets?
4. How should the SKA pulsar case be split between SKA low and high (e.g., how much timing/searching on each telescope)?
5. Can SKA-low observations be used to monitor dispersion measure variations and remove them from SKA-mid observations?

Conclusions

1. Pulsar astronomy is a very exciting research area. Key science projects relate to pulsars on existing telescopes (Parkes, …), new telescopes (FAST, …) and future telescopes (SKA)
2. Very high possibility of new discoveries
   - New pulsars
   - New transient sources
   - Currently unknown objects
   - Ultra-low-frequency gravitational waves
3. Pulsar observations have practical applications
   - Testing theories of relativity
   - Navigation
   - Improving time standards
4. Pulsar research is fun!